Refinement of Bulk Scattering Models for the Remote Sensing of Ice Clouds

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Purpose: Refine ice cloud bulk scattering models for various sensors to incorporate recent advances in ice particle simulations and *in situ* microphysical measurements. For purposes of data fusion and cloud product intercomparison, the models are derived for each instrument consistently.

Goals:

a. Further refine models used by MODIS for Collection 5.
b. Continue to integrate in situ measurements and light scattering advances.
c. Incorporate new ice habits.
d. Develop models for active/passive sensors using consistent methodology.
e. Develop models for use with instruments that measure radiances from the visible to far-infrared wavelengths.
f. Provide some measure of uncertainty for each property in the models for use with optimal estimation methods.
g. Apply models in data fusion research (e.g., MODIS + AIRS; POLDER + MODIS)

Models are available at http://www.ssec.wisc.edu/~baum

In situ Data - Particle Size Distributions

Gamma size distribution* has the form:

$$N(D) = N_o D^{\mu} e^{-\lambda D}$$

where D = *max diameter*

N_o = *intercept*

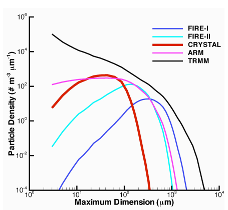
μ = *dispersion*

λ = *slope*

The intercept, slope, and dispersion values are derived for each PSD by matching three moments (specifically, the 1st, 2nd, and 6th moments)

Note: when $\mu = 0$, the PSD reduces to an exponential distribution

****Heymsfield et al., Observations and parameterizations of particle size distributions in deep tropical cirrus and stratiform precipitating clouds: Results from in situ observations in TRMM field campaigns. J. Atmos. Sci., 59, 3457-3491, 2002.***



Synoptic cirrus characteristics
- *Size sorting more pronounced*
- *Small crystals at cloud top*
- *More often find pristine particles*

Convective cirrus characteristics

Form in an environment having much higher vertical velocities
- *Size sorting is not as well pronounced*
- *Large crystals often present at cloud top*
- *Crystals may approach cm in size.*
- *Habits tend to be more complex*

Field Campaign Data Used to Date

Field Campaign	*Location*	*Instruments*
FIRE-1 (1986)	Madison, WI	2D-C, 2D-P
FIRE-II (1991)	Coffeyville, KS	Replicator
ARM-IOP (2000)	Lamont, OK	2D-C, 2D-P, CPI
TRMM KWAJEX (1999)	Kwajalein, Marshall Islands	2D-C, HVPS, CPI
CRYSTAL-FACE (2002)	Flight track off coast of Nicaragua	2D-C, VIPS

Probe size ranges (at least, usable ranges):

2D-C, ~100-1000 µm
2D-P, 200-6400 µm
HVPS (High Volume Precipitation Spectrometer), 200–5000 µm
CPI (Cloud Particle Imager), 20-2000 µm
Balloon-borne Replicator, 10-800 µm
VIPS (Video Ice Particle Sampler), ~10-350 µm

Other probes now being used (e.g., TC-4):

2DS (new probe, similar to 2DC with faster optics), 20–2000 µm
Cloud Imaging Probe (CIP), 25-1600 µm
Precipitation Imaging Probe (PIP), 100-6400 µm
Small Ice Detector (SID-2), ~1-50 µm

New field Campaign data will soon be provided from:

Pre-AVE: Pre-Aura Validation Experiment (2004)

TWP-ICE: Tropical Western Pacific International Cloud Experiment (2005-2006)

NASA TC-4: Tropical Composition, Cloud and Climate Coupling (2007)

ICE-L: Ice in Clouds Experiment – ice cloud nucleation measurements (2007)

Next generation ice models will incorporate
- advances in measurement techniques
- better characterization of the number and shape of small ice particles
- comprehensive set of microphysical measurements from combination of probes
- more guidance on ice habits and their characteristics
- more guidance on realistic habit mixtures

Single scattering Databases for Various Ice Habits

Visible/Shortwave Infrared (VIS/SWIR) Database

Ice particle habits:
Hexagonal plates
Solid and hollow columns
Aggregates
Droxtals
3D bullet rosettes

45 size bins ranging from 2 to 9500 µm

Spectral range: Currently 0.4 to 2.2 µm with a few gaps

Planned updates:
Spectral range: 0.3 to 3 µm
Include hollow bullet rosettes
Include surface roughening (none, moderate, heavy)
Explore hopper growth
Explore more realistic aggregate particle

Midwave Infrared/IR/Far-IR (MWIR/IR/Far-IR) Database

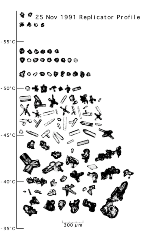
Ice Particle Habits:
Hexagonal plates
Solid and hollow columns
Aggregates
Droxtals
3D bullet rosettes

45 size bins ranging from 2 to 9500 µm

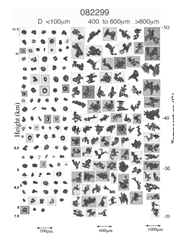
Spectral range: 100 to 3250 cm^{-1} at 1-cm^{-1} resolution

Planned updates:
Include hollow bullet rosettes
Include surface roughening (none, moderate, heavy)
Explore hopper growth

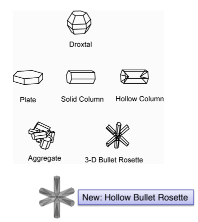
Properties for each habit/size bin include volume, projected area, maximum dimension, single-scattering albedo, fraction of delta-transmission energy (VIS/SWIR only), asymmetry factor, extinction/scattering cross sections as well as extinction efficiency.



Synoptic Cirrus

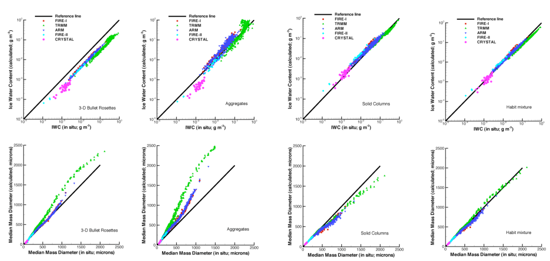


Tropical Anvil Cirrus



Ice Habits in Scattering Calculations

Ice Particle Habit Percentages Based on Comparison of Calculated to In-situ D_m and *IWC*



Since each idealized ice particle has a prescribed volume, and hence mass, we can calculate *IWC* (ice water content) and D_m (median mass diameter) for each PSD.

Subsequently, we can compare the *IWC* and D_m values computed with the simulated ice habits to those values estimated for each PSD from the techniques developed by Heymsfield and colleagues. This provides a constraint on the prescribed habit mixture.

New guidelines for habit mixture

4-5 size ranges defined by maximum dimension

Droxtals: used only for smallest particles

Aggregates: will phase out until new aggregate habit is defined (plates, not columns)

Plates: used only for particles of intermediate size

Use more hollow than solid columns/plates/rosettes

Current ice particle habit mixture

Max length < 60 µm
100% droxtals

60 µm < Max length < 1000 µm
15% bullet rosettes
35% hexagonal plates
50% solid columns

1000 µm < Max length < 2500 µm
45% solid columns
45% hollow columns
10% aggregates

Max length > 2500 µm
97% bullet rosettes
3% aggregates

Changes to ice particle habit mixture

Max length < 10 µm
100% droxtals

10 µm < Max length < 60 µm
Droxtals + bullet rosettes + columns + plates

60 µm < Max length < 1000 µm
Primarily hollow bullet rosettes/columns + plates

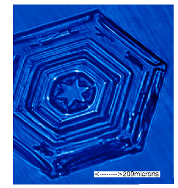
1000 µm < Max length < 2500 µm
Primarily hollow particles (columns + bullet rosettes)

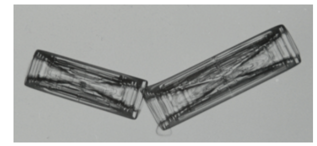
Max length > 2500 µm
Primarily hollow bullet rosettes

Explore new areas

Hopper Growth

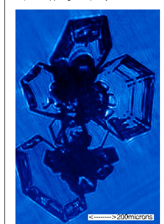
We have typically treated ice particles as having smooth or rough surfaces. A more realistic approach should consider the "hopper instability". Surface effects dominate growth when the particles are small. As the particle grows, the corners and edges grow faster than in the interior of the particle (greater access to water molecules). Result: hollow particles with a "stair-step" appearance.

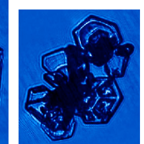




Aggregate of plates

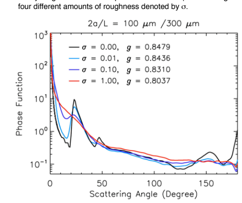
Our previous assumption that an aggregate is composed of solid columns needs to be revisited – the particle is too dense. The use of hollow plates (with hopper growth) may be more realistic.





Surface roughening

Previous models assumed that particle surfaces are smooth, except for the aggregate. The new database will include both moderate and heavy roughness. The example below is at 0.66 µm wavelength with four different amounts of roughness denoted by σ.



Yang et al., Uncertainties associated with the surface texture of ice particles in satellite-based retrieval of cirrus clouds: Part II. Effect of surface roughness on retrieved cloud optical thickness and effective particle size. In press, IEEE Trans. Geosci. Remote Sens.

Revised Data on Ice Optical Constants

Previous calculations used the ice optical constants (refractive indices) in Warren (1984), but in this latest compilation by Warren and Brandt (2008), the values for the imaginary part of ice refractive index at some wavelengths are quite different. The absorption of radiation of ice crystals is determined by the imaginary part of ice refractive index, and this could have a large impact on the remote sensing of ice cloud properties. This updated compilation of the ice index of refraction alone warrants a full recalculation of the ice habit scattering properties across the spectrum.

Warren, S.G. and R.E. Brandt: Optical constants of ice from the ultraviolet to the microwave: a revised compilation. Submitted to J. Geophys. Res., 2008

Selected References

Baum, B. A., A. J. Heymsfield, P. Yang, and S. T. Bedka, 2005a: Bulk scattering models for the remote sensing of ice clouds. 1: Microphysical data and models. *J. Appl. Meteor.*, **44**, 1885-1895.

Baum, B. A., P. Yang, A. J. Heymsfield, S. Platnick, M. D. King, Y.-X. Hu, and S. T. Bedka, 2005b: Bulk scattering models for the remote sensing of ice clouds. 2: Narrowband models. *J. Appl. Meteor.*, **44**, 1896-1911.

Baum, B. A., P. Yang, S. L. Nasiri, A. J. Heidinger, and J. Li, 2007: Bulk scattering properties for the remote sensing of ice clouds. 3: High resolution spectral models from 100 to 3250 cm^{-1}, *J. Appl. Meteor. Clim.,* **46**, 423-434.

Field, P. R., A. J. Heymsfield, A. Bansemer, 2006: Shattering and particle interarrival times measured by optical array probes in ice clouds. *J. Atmos. Ocean. Technol.*, 23, 1357-1371.

Schmitt, C. G. and A. J. Heymsfield, 2007: On the occurrence of hollow bullet rosette and column shaped ice crystals in mid-latitude cirrus. *J. Atmos. Sci.,* **64**, *4514-4519.*

Yang, P., H. Wei, H. L Huang, B. A. Baum, Y. X. Hu, M. I. Mishchenko, and Q. Fu, 2005: Scattering and absorption property database of various nonspherical ice particles in the infrared and far-infrared spectral region. *Appl. Opt.,* **44**, 5512-5523.

Yang, P., L. Zhang, G. Hong, S. L. Nasiri, B. A. Baum, H.L. Huang, M. D. King, and S. Platnick, 2005: Differences between Collection 4 and 5 MODIS ice cloud optical/microphysical products and their impact on radiative forcing simulations. *IEEE Trans. Geosci. Remote Sens.*, Vol. 45, No. 9, 2886-2899.

Yang, P., Z. Zhang, G. W. Kattawar, S. G. Warren, B. A. Baum, H.-L. Huang, Y.-X. Hu, D. Winker, and J. Iaquinta: Effect of cavities on the optical properties of bullet rosettes: Implications for active and passive remove sensing of ice cloud properties. In press, *J. Appl. Meteor. Clim.*